One-Dimensional Modeling of Incision through Reservoir Deposits

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Abstract: A one-dimensional sediment transport model (GSTAR-1D) is used to simulate a laboratory experiment of incision through a reservoir delta deposit. The model allows the user to specify the erosion width through the deposit as a function of the flow rate. The model is shown to predict the vertical incision and downstream sediment load with reasonable accuracy if the erosion width is specified correctly. Sensitivity tests to the transport equation parameters, erosion width, and angle of repose are conducted. The sediment loads exiting the dam are shown to be sensitive to the critical shear stress, but are relatively not sensitive to changes to the erosion width and angle of repose. Further work on modeling of bank erosion is necessary to more accurate predict the long term evolution of reservoir deposits.

1. INTRODUCTION

A reservoir draw down triggers many sediment processes. The initial drawdown causes an increase in hydraulic gradient that provides the energy for a rapid incision through the delta upstream of the dam. This incision may progress upstream as a head cut or as a diffusive front. The sediment eroded is then re-deposited into the receded delta. In some cases, the sediment eroded from the delta may form turbidity currents as it enters the reservoir. As the incision process continues, the steep banks can fail from becoming too steep or from undercutting. The dewatered delta sediments will begin to consolidate and significant changes in volume may result. If sufficient water is stored within the surrounding geology, there will be a hydraulic gradient through the sediments. The groundwater hydraulic gradient is transverse to the flowing water in the river and may cause slumping of the sediment towards the incising channel. Then, after the initial incision, a widening process may begin. The widening may occur through meandering processes and/or the occurrence of flood flows. A channel is eventually formed through the deposits that will be composed of a main channel and floodplains. However, depending upon the width of the reservoir delta, much of the original reservoir deposit may remain.

The above processes are quite complicated and presently no numerical model can reliably simulate all these processes. At this stage, a step-wise approach is suggested to develop models for these processes. As a first step, this paper presents a one-dimensional (1D) model for the incision process and it is tested against laboratory data.

2. TEST OF 1D MODEL

The 1D model tested was GSTAR-1D (Generalized Sediment Transport for Alluvial Rivers – One Dimension), Reclamation (2005). GSTAR-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. It is able to compute water surface profiles in single channels, dendritic, and looped network channels. It has both steady and unsteady flow models, steady and unsteady sediment models. GSTAR-1D uses standard step method to solve the energy equation for steady gradually varied flows and the Exner equation to solve the sediment routing equation. Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates are simulated. The notation of an active layer, which allows selective erosion, provides an appropriate framework to simulate the bed armoring. Non-cohesive sediment transport equations and cohesive sediment physical processes are applied to calculate the sediment deposition and erosion. The most recent version can be downloaded at: www.usbr.gov/pmts/sediment.

2.1 EXPERIMENT DESCRIPTION

Experimental data was used to test the validity of GSTAR-1D in predicting the erosion of reservoir deposits following dam removal or during reservoir sluicing. Cantelli et al. (2004) performed experiments at the University of Minnesota to simulate the removal of dam. A flume with a slope of 0.018 and a width of 0.061 m was filled with sediment to replicate the sediment deposit behind a dam. The sediment was uniform with a d_{50} of 0.8 mm, which is coarse sand. The maximum depth of the sediment deposit was approximately 0.12 m. A channel 1 cm deep and 27.5 cm wide was cut in the middle of the deposit to ensure that the erosion occurred in the middle of the channel. A flow of 0.3 l/s was allowed to erode the deposit. The sediment feed was continued at a rate of 0.002 kg/s during the experiment. This was calculated to be an equilibrium supply rate at the given slope and width.

A unique feature of these experiments was the precise measurement of the bed profile and cross section width upstream of the dam while the flow eroded the deposit.

2.2 MODEL INPUT

The input data for GSTAR-1D consists of geometry data, flow data, sediment boundary conditions, and sediment transport parameters. The geometry was taken from the description of the experimental set up. Cross sections were spaced 10 cm apart in the numerical model. Each cross section was represented by points spaced 1 cm transverse to the flow. The Manning's roughness coefficient was assumed to equal 0.025. A single sediment size of 0.8 mm was assumed. The flow rate and sediment feed rate were taken from the experiment values.

Parker's (1990) surface based transport formula was used to predict sediment transport capacity. Parker (1990) developed an empirical bed-load transport function based on the equal mobility concept and field data. However, a single sized sediment was used in these experiments and therefore the hiding and equal mobility features of this transport model are not important.

Two parameters must be defined by the user to use Parker's equation: the non-dimensional critical shear stress and the hiding factor (θ_c and α, respectively). Ideally, these values should be fit to data of the stream being simulated. However, in the absence of data several references provide guidance, such as Buffington and Montgomery (1997). In the simulations performed here, a value of 0.03 was used for θ_c, which is near the values recommended in Buffington and Montgomery. As a sensitivity test, a value of 0.04 was also simulated for the value of θ_c. The value of α is not important because only a single size class is being simulated.

The erosion width is an important parameter in estimating the erosion details. Because one-dimensional models do not have a shear stress that varies across a cross section, it is difficult to estimate the non-uniform erosion that occurs during incision. Cantelli et al. (2004) observed a rapid narrowing of the channel followed by a gradual widening. The narrowing was caused because the vertical erosion in the middle of the channel was faster then the banks could supply additional sediment. The highest shear stresses were in the middle of the channel and therefore the highest erosion rates occur there. The banks initially do not supply sufficient sediment to maintain a wide section and the section narrows. Eventually, the rapid incision slows and the bank erosion continues and the section starts to widen.

GSTAR-1D does not directly simulate lateral transport of sediment because it is a one-dimensional model, however, it empirically accounts for the processes involved by using a relationship between erosion width and flow rate and an angle of repose condition for bank stability. The following equation is used in GSTAR-1D to determine the erosion width:

$$W_e = aQ^b \tag{1}$$

where W_e is the erosion width, Q is the stream flow, and a and b are user defined constants. The boundaries of the erosion width are determined by first finding the centroid of the cross section, then assuming that W_e is apportioned equally on either side. The erosion width for the experiments of Cantelli et al. (2004) began at approximately 26 cm. The width decreased rapidly to less than 5 cm near the dam face, but at about 40 cm upstream of the dam face the width was not less than 17 cm. After 2.5 minutes the width throughout the entire flume was greater than 17 cm and began to gradually increase. For the simulation, the erosion width was set to 24 cm for the flow rate of 0.0003 m^3/s (a = 12, b = 0.5). As a sensitivity test, an erosion width of 20 cm was also simulated.

Bank failure is simulated using an angle of repose condition. GSTAR-1D requires an angle of repose below and above water. The angle of repose above water was set to 70 degrees because the banks were near vertical during the experiment. Because the sand was saturated before the experiment and the water was only a few centimeters below the banks, capillary forces were significant between the sand particles and enabled the banks to remain almost vertical. Based upon the video footage from the experiment, the bank collapse was seen to occur as the banks were undercut. The angle of repose below water is more difficult to determine. The shape of the below water channel is a function of the stream wise and transverse sediment transport. The below water angle of repose was set to 25 degrees. To test the sensitivity of the model to the angle of repose, simulations were also run for an angle of repose equal to 35 degrees above and below water.

A summary of the input parameter used in the simulations is given in Table 1. The simulations are referred to Simulations 1 through 4 with Simulation 1 being referred to as the base run.

Table 1. Summary of GSTAR-1D Input Parameters. Values changed from Base Run (Simulation 1) are italicized.

	Simulation			
Parameter (units)	**1**	**2**	**3**	**4**
Critical Shear Stress (-)	0.03	*0.04*	0.03	0.03
Erosion Width (cm)	24	24	*20*	24
Angle of Repose, Above Water (degrees)	70	70	70	*35*
Angle of Repose, Below Water (degrees)	25	25	25	*35*

2.3 MODEL RESULTS

The simulated results from GSTAR-1D were compared against the experimental data of Run 6 of Cantelli et al. (2004). The simulated and measured bed elevations are shown in Figure 1. Overall, the agreement between the measured and simulated is satisfactory. It should be remembered, however, that the agreement was improved by calibrating the critical shear stress in Parker's bed load equation. The calibrated value (0.03) is a typical value applied in field situations but may vary based upon particle shape and form roughness in the river. The only significant disagreement between measured and predicted values is in the initial stages of channel formation where the initial incision rates were slightly under-predicted. Because the model does not simulate all processes involved in the erosional narrowing observed in the experiments, the simulated initial channel widths are larger than the measured ones. Therefore, the simulated bed elevations decrease more slowly than the measured ones.

The sediment loads are shown in Figure 2. Initially, the simulated sediment loads fit the measured relatively well. However, the simulated sediment loads at the dam face do not decrease as rapidly as the measured loads. The measured sediment loads decrease to approximately the feed rate values after approximately 600 seconds. This would indicate that after 600 seconds there is no net erosion or deposition between the location of the feed and the dam face. That conclusion is in contradiction to the bed profile and top width evolution. Both the bed profile and the top width indicate that erosion continues throughout the course of the experiment. Therefore, one would expect that the sediment discharge at the dam face should be higher than the feed rate. It is expected that there is a bias in the measured sediment discharges at the dam face.

The evolution of the wetted top width is shown in Figure 3. The 1D model does not predict erosional narrowing because no transverse sediment transport is modeled. The erosion is primarily vertical with only a minor widening because the angle of repose above water was assumed relatively large. There were no cross sectional data to compare the model against.

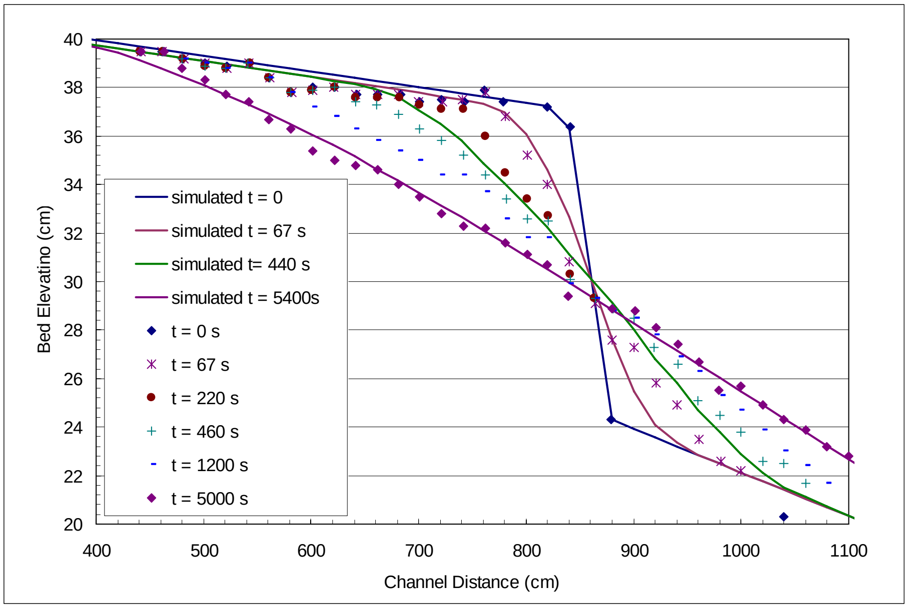

Figure 1. Comparison between Run 6 of Cantelli et al. (2004) and GSTAR-1D for the bed profile, base run, Simulation 1.

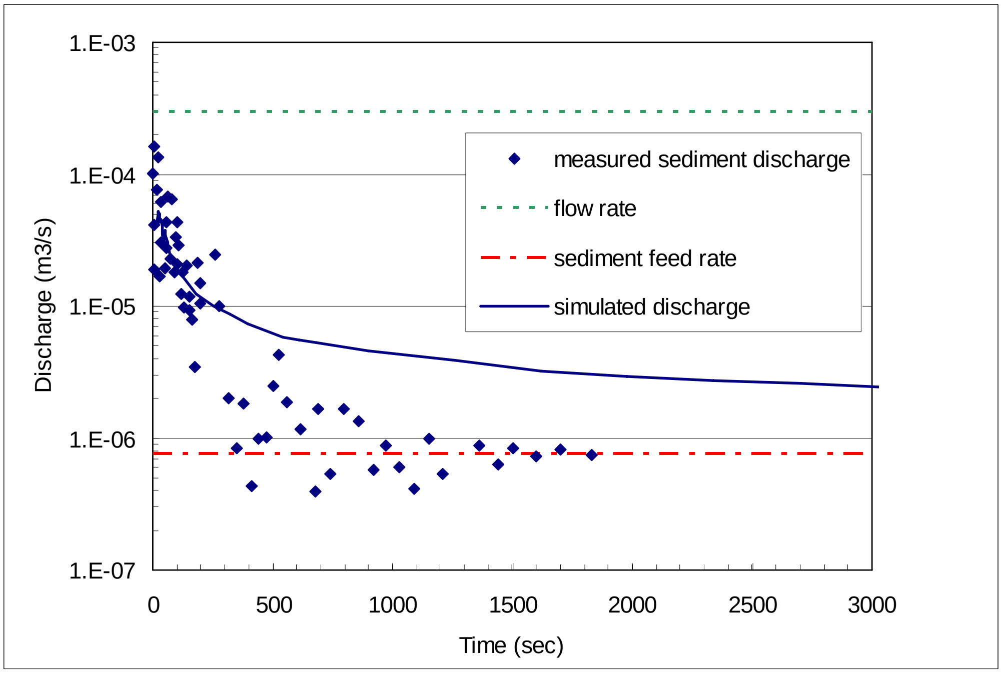

Figure 2. Comparison between Run 6 of Cantelli et al. (2004) and GSTAR-1D for the sediment discharge at the dam face, base run, Simulation 1.

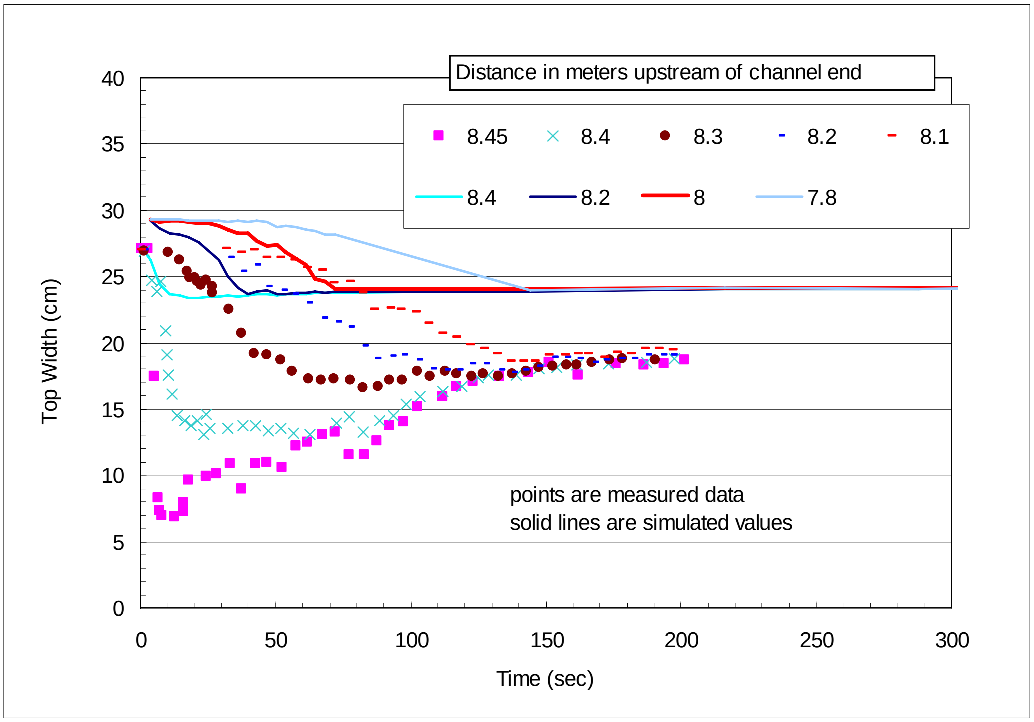

Figure 3. Comparison between Run 6 of Cantelli et al. (2004) and GSTAR-1D for the wetted top width, base run. Solid lines are simulated values. Points are measured. Simulation 1.

2.4 SENSITIVITY TO CRITICAL SHEAR STRESS

The critical shear stress was increased to 0.04 and the same simulation was performed. This simulation is termed Simulation 2. A comparison of Simulations 1 and 2 is given for the bed profile (Figure 4) and for the sediment discharge at the dam face (Figure 5).

Because the critical shear stress enters directly into the sediment transport formula, Eq (1), raising the critical shear stress will decrease the simulated sediment transport rates. The decrease in the sediment transport rates causes sediment to erode more slowly. Therefore, the bed elevations of Simulation 2 are higher than for Simulation 1 upstream of the dam. The predicted sediment loads at the dam face are also lower in Simulation 2 than for Simulation 1.

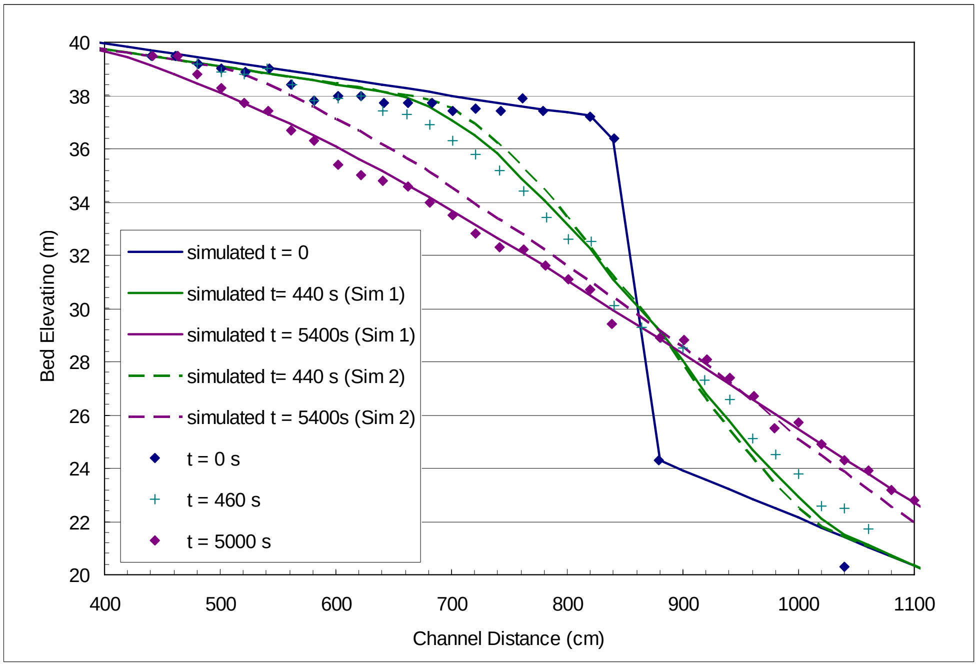

Figure 4. Sensitivity of bed profile to critical shear stress.

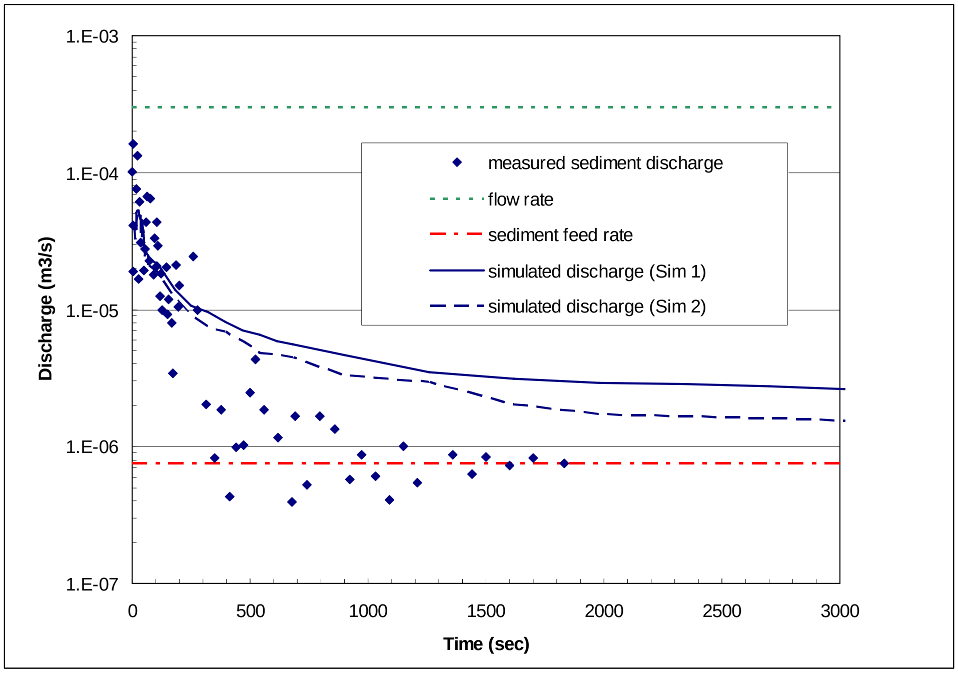

Figure 5. Sensitivity of sediment discharge at dam face to critical shear stress.

2.5 SENSITIVITY TO EROSION WIDTH

The erosion width was decreased to 20 cm and the simulation results from this simulation (Simulation 3) are compared against the base run, Simulation 1. Decreasing the erosion width causes the vertical incision to occur more rapidly (Figure 6). However, the sediment loads at the dam face are relatively unaffected by the decrease in erosion width. The sediment loads did not change significantly from Simulation 1 because even though the vertical incision occurred more quickly, the width of erosion was less and therefore approximately the same volume of sediment was removed (Figure 7).

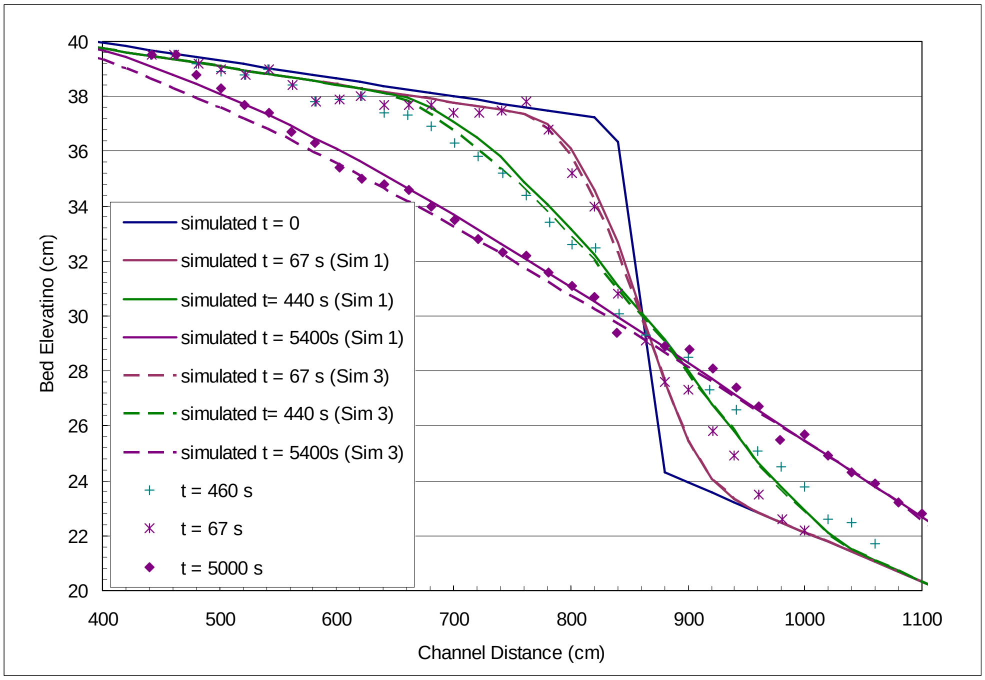

Figure 6. Sensitivity of bed elevation to erosion width.

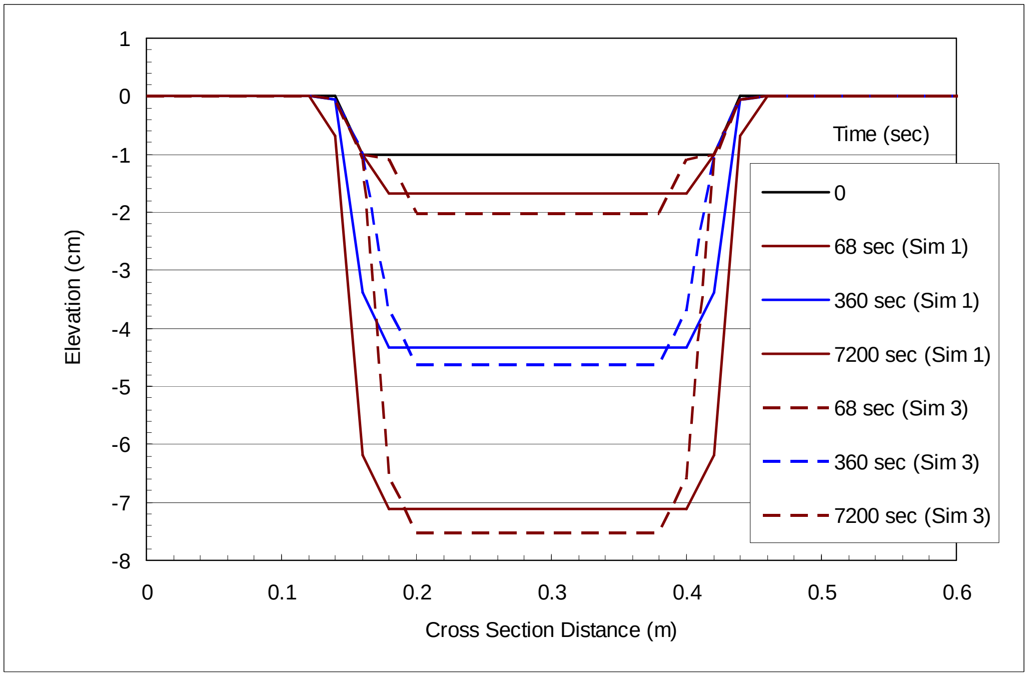

Figure 7. Sensitivity of cross section shape to erosion width.

2.6 SENSITIVITY TO ANGLE OF REPOSE

The above and below angle of repose were set to 35 degrees. This simulation is termed Simulation 4 and is compared against Simulation 1. The difference in bed elevations was relatively small, 3 mm or less, but Simulation 4 consistently showed less erosion than the base run. However, the sediment loads at the dam face were relatively unaffected. The sediment loads were relatively unaffected because even though the vertical incision was less in Simulation 4, the horizontal widening was greater because of the smaller angle of repose.

3. DISCUSSION

Several important issues need to be addressed when applying a 1D model to simulate dam removal. Many sediment processes are ignored in a 1D model because the 1D model does not directly simulate transverse sediment movement and calculates a single average shear stress for a cross section. To empirically account for these factors, an appropriate erosion width and angle of repose should be specified. In GSTAR-1D, the erosion width is specified as a function of flow rate. HEC-6T (MBH Software, 2001) requires a similar specification and DREAM (Stillwater Sciences, 2002) requires a fixed base width. Often the erosion width is determined based upon the upstream and/or downstream river width. As a first estimate, equation (1) could be fit to the upstream and downstream river channels. If the fit coefficients of equation (1) for the upstream and downstream river channels are significantly different, some judgment may be necessary as to the most appropriate values.

The angle of repose can be specified based upon sediment type. The angle of repose for non-cohesive sediments these values are relatively well bounded. However, for cohesive sediments, the angle of repose may be difficult to determine, or may not be a constant value. It is likely that the stable angle for cohesive soils will be a function of the groundwater gradients in the sediments. Future research is necessary to address this issue. Even though the transverse variation of shear stress and bed load are ignored, in many cases the loss of these details may not significantly alter the uncertainty of the erosion estimates. The greatest uncertainty may still reside in the calculation of the streamwise sediment transport.

Additional research is needed to develop appropriate models of the long term bank erosion. It is important in determining the concentrations downstream of the dam. Because the reservoir is usually much finer than the river bed sediment, the reservoir may potentially act as a source of fine sediment for many years as the banks slowly erode. As shown in the experiments of Cantelli (2004), bank caving occurs after the initial channel incision as the flowing water undermines the steep banks. This process is difficult to model with a 1D model and no readily available model exists. In most cases, it is assumed that bank erosion after the first few years will be limited to large storm events. However, there is often no quantitative method applied to determining which events will cause additional bank erosion. It may be feasible to use a method similar to that employed in CONCEPTS (Langendoen, 2000) where the geotechnical strength of the bank is evaluated as well as the shear stress applied to the bank.

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